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Abstract

Approximately one billion people globally live in informal settlements with a large potential fire risk, where a single dwelling fire may result in a very large urban conflagration leaving hundreds, if not thousands, of people homeless. What is not well understood, however, is how fires in informal settlement dwellings develop and spread, and what influence the dwelling boundary has on these two areas. In this work, four different real-scale compartments were constructed and ignited under a large fire calorimeter hood. The cases include a typical thin metal-walled dwelling (baseline), a no leakage dwelling, a dwelling lined with cardboard and a dwelling with highly insulated walls. The fuel locations, fuel loads of 25 kg/m^2, ignition method and ambient conditions were kept identical in four experiments. Important parameters of compartment fire development, such as heat release rate, gas temperatures, fuel mass loss rate, wall and ceiling temperature were recorded. To investigate the fire spread mechanism between dwellings, the incident radiation heat flux around the dwellings and projection flame length were measured as well. It was found that the boundary conditions in informal settlement significantly affect the fire dynamics and fire spread of informal settlement, and that current analytical/empirical equations are not capturing accurately experimental observations.

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1. Introduction

Urbanisation poses a massive sustainability challenge for cities in terms of infrastructure, housing, and basic services, amongst other issues [1]. It is estimated that 55% of the world's population now live in urban areas [2], and that approximately 30% of the urban population live in informal settlements in developing regions [3]. Over one billion people across the globe live in informal shack settlements, and this number is ever increasing. Many of these informal settlements (i.e. shantytowns, favelas, slums) are at constant risk of lethal, large-scale destructive fires due to flammable construction materials, heating and cooking methods, shack proximity, a lack of effective fire services, etc. Thus, the big fire disasters in informal settlement occurred frequently in global south, such as Kijiji, Kenya, January 2018 (6000 homeless); Dhaka, Bangladesh, March 2018 (1000 dwelling destroyed, 4484 homeless); Lambayog, Philippines, July 2018 (5000 dwellings destroyed); Khayelitsha of Cape Town, South Africa, October 2018 (1000 dwelling destroyed, 4000 homeless). In August 2019, a massive fire swept through a slum in the capital of Bangladesh, Dhaka, which is the biggest informal settlement fire in recent years leaving an estimated 15,000 homeless [4].

With the increase of urban populations and the increasing frequency of informal settlement fires in areas such as Cape Town; deaths and morbidity are likely to increase. There is an imperative, therefore, to understand better and mitigate against these fire risks whilst being sympathetic to their complex social and political structures [5, 6].

One of those risks is the relatively unknown influence of the types of construction commonly found in these informal settlements on the fire development within dwellings and fire spread mechanisms between dwellings. Informal settlement dwellings are usually hand-built structures, usually made from timber beams and posts, and clad with thin recycled steel or timber panels. This, therefore, creates a thermally-thin compartment with leaky boundaries by connecting corrugated sheet with timber column or beam [7].

Recent research efforts have explored different methods to understand the fire spread and fire development issues. GIS (Geographic Information System) has been employed to conduct case study of detecting the fire occurrence in the informal settlement and the safe separation distance in historical fires [8, 9]. In addition, different scales of experiments [10, 11] were conducted to provide the database of the burning characteristics of materials commonly found in informal settlements. Experimental work has looked at fire development and spread in steel clad and timber clad dwellings [10] with relatively successful attempts to model these using FDS [12]. However, these models of up to three dwellings are computationally heavy and not practicable for modelling entire settlements [13]. Fire Dynamic Simulator (FDS) has also been used to investigate and propose risk mitigation methods, including the effect of horizontal opening on dwellings [14] and fire(brand) separation wall between informal settlement blocks [15].

In all of the previous research, the boundary conditions (i.e. material composition of the walls and their proximity to the nearest neighbour) of these dwellings were found to be of great importance to the fire development and spread in real situations. The previous full-scale informal settlement experiments with timber and steel clad structures [7, 10] were conducted outdoors with; limited internal and external boundary condition variations; under the influence of wind (albeit at low speeds); and leakages caused by the unavoidable connection gap of galvanized steel sheeting.

Therefore, there is a necessity to understand the influence of the compartment boundary on the fire development and fire spread characteristics in a systematic and highly controlled way. Fire development characteristics include heat release rate, gas-phase temperatures, wall and ceiling temperatures, flow at openings, and time to flashover; whilst fire spread characteristics include heat fluxes and flame lengths from openings. To model these internal and external fire dynamics of informal settlements dwellings properly, we need to understand and quantify these characteristics specifically accounting for: the influence of leakage; the influence of combustible wall linings; and the influence of thermally thin boundaries, with high fidelity and reasonably similar conditions of fuel load, dwelling size and surrounding environment.

To achieve this understanding and quantification, four informal settlement dwelling fires, with different wall and insulation conditions, were performed. All the dimensions were kept identical to the ISO 9705 room. A benchmark dwelling, without lining materials, was designed and burnt first, and then three different experiments with different lining, leakage and insulation conditions, were conducted.

2. Experimental configuration

2.1 Dwelling design

Four single dwellings with an identical dimension to ISO 9705 room (3.6 m×2.4 m×2.4 m), were constructed, selected from a series of 13 experiments investigating the fire dynamics of informal settlement dwellings. Cement boards with a thickness of 8 mm were laid on the floor and the structure erected on top. The walls and ceiling were made from corrugated galvanized steel sheets with a thickness of 0.51 mm attached to the timber frame. The timber lengths in the frames were 0.038 × 0.089 m in cross-section and constructed using a combination of gang nails and self-tapping screw, with sheeting attached through predrilled holes using wide flanged screws. The design and materials were adopted to model common informal settlement dwellings typology, as shown in Fig. 1. Two openings were designed including a door with internal dimensions of 2.0 m (height) × 0.8 m (width) and a window of internal dimensions 0.6 m × 0.6 m, both located in the front long wall, 0.7 m and 2.0 m away from the right front corner, respectively. It should be noted that there is no door and glass window in the experiments thus the opening factor between experiments was not changed.

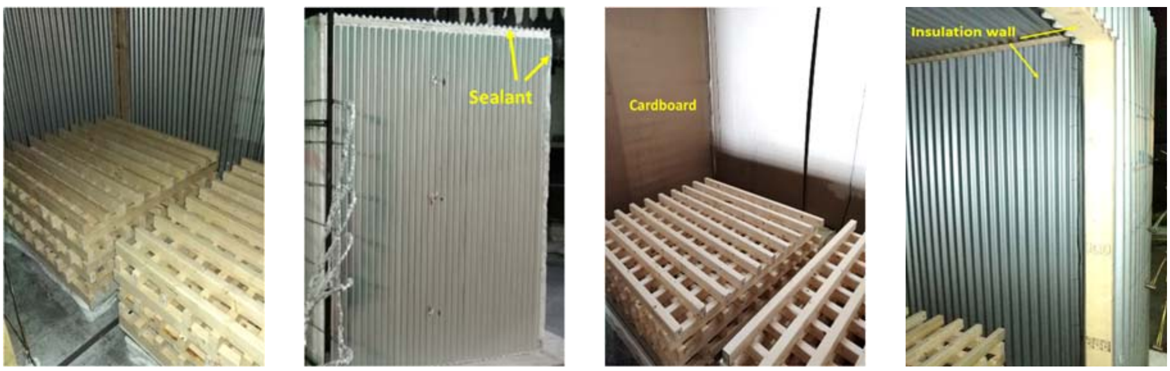
a) b)

Fig. 1. The structural dimension of the dwellings; a) from informal settlements in Cape Town, and b) our test specimen dwelling.

The fire load density within informal settlement dwellings varies highly, however, according to the local firefighters [10]. According to surveys conducted in South Africa, the average fuel load is 410 MJ/m^2 with a standard deviation of 140 MJ/m^2 [16]. Some may reach the value of 1000-2000 MJ/m^2 as residents put a large number of combustible materials and fuel in the very limited space for which they have to compete.

Two wood cribs (each is 112 kg) were placed at the centre of the compartment with a separation distance of 0.18 m. Each crib consisted of 7 layers of 10 sticks with a dimension of 0.038 × 0.064 × 1.219 m^3 and a density of 540 kg/m^3. The sticks were stacked with the short edge of the cross-section being horizontal. Thus, the fuel load of the compartment was 25 kg/m^2 with consideration of floor area of 3.632 m (143 inches) by 2.438 m (96 inches) (errors caused by the US unit and metal sheet manufacture). Assuming a heat of combustion of timber of 17.5 MJ/kg [17], the fuel load in this work is approximately 437.5 MJ/m^2. The fuel load and distribution were kept identical in the four experiments. Fig. 2(a) shows a view inside a compartment with the wood crib prior to ignition. The ignition source was Gasoline-87 soaked mop head strips in a small plastic bag, and four bags were distributed at four bottom corners of each crib (i.e. 8 bags in total per experiment).

The impact of four different boundary conditions on the internal and external fire dynamics are investigated in the four experiments summarized in Table 1 and presented in Fig. 2. The first experiment is considered as the Baseline (BL) from which comparison will initially be made. The second experiment Baseline - No Leakage (BL-NL) aims to understand the impact of the leakage seen at the connection between the wood frame and corrugated galvanized steel sheets on the fire dynamics of these dwellings. This was accomplished by attaching ceramic fibre blanket to the timber frames with fire cement before the steel sheets were attached. The third experiment Baseline + Cardboard Lining (BL+CL) investigates the impact of lining the four sidewalls with 5 mm thick cardboard, which is commonly used as lining materials as per the authors' survey. In the fourth and final experiment Baseline + High Insulation (BL+HI) presented here we investigate the impact of increasing the insulative properties of the vertical boundary walls. This was achieved by adding additional studs to the wall frames and adding Rockwool (R 23) with a thickness of 14 cm between the studs. An extra internal layer of steel sheeting was added so as to have approximately the same internal surface area of galvanised steel being exposed to the fire, with the same properties of the baseline experiment. It should be noted that no insulation was placed on the roof.



a) Experiment 1- BL	b) Experiment 2 – BL-NL	c) Experiment 3 – BL+CL	d) Experiment 4 – BL+HI

Fig. 2. View of the compartments prior ignition.

Table 1. The summary of four full-scale experiments.

Experiment*	Wall materials	Leakage	Lining materials
BL	Metal sheet	Yes	No
BL-NL	Metal sheet	No	No
BL+CL	Metal sheet	Yes	Cardboard
BL+HI	Metal-rockwool-metal composite	Yes	No

* BL represents Baseline; BL-NL for Baseline - No Leakage; BL+CL for Baseline + Cardboard Lining; BL+HI for Baseline + High Insulation.

2.2 Measurements

As illustrated in Fig. 3, two 1.0 m × 1.0 m scales with 300 kg measurement range and 0.1 kg precision were placed in the middle of the dwelling to respectively measure the mass loss of the two wood cribs. A protective platform of 1.219 × 1.219 m was placed upon each scale and carried the timber cribs. The sides and cables of the scales were protected with ceramic blankets.

Six thermocouple (TC) trees were suspended from floor to ceiling, one in each of the corners and two along the centreline of the long axis walls. Each thermocouple tree had 10 Inconel sheathed Type-K thermocouples with a tip diameter of 1.0 mm. The spacing of the thermocouples is shown in Fig. 3. To measure the metal boundary temperatures, three thermocouples were attached on the outside of the side walls without openings with high temperature cement and aluminium foil tape at the heights of 0.4, 1.2 and 2.0 m; meanwhile three additional ones were fixed at the roof (outside surface) along the centreline (short axis) of the roof 76 cm (30 inches) or half length of roof away from the roof edge.

Along the vertical centreline of the door, six bi-directional flow probes with an associated thermocouple were fixed for gas velocity measurements; three more were placed at the vertical centreline of the window. The spacing of the flow probes and associated thermocouples are shown in Fig. 3. In addition, in-house gas analysers were fixed at the left back corner (10 cm away from each wall and 5 cm from the ceiling) or at the upper window location to measure the concentration of the oxygen and carbon dioxide.

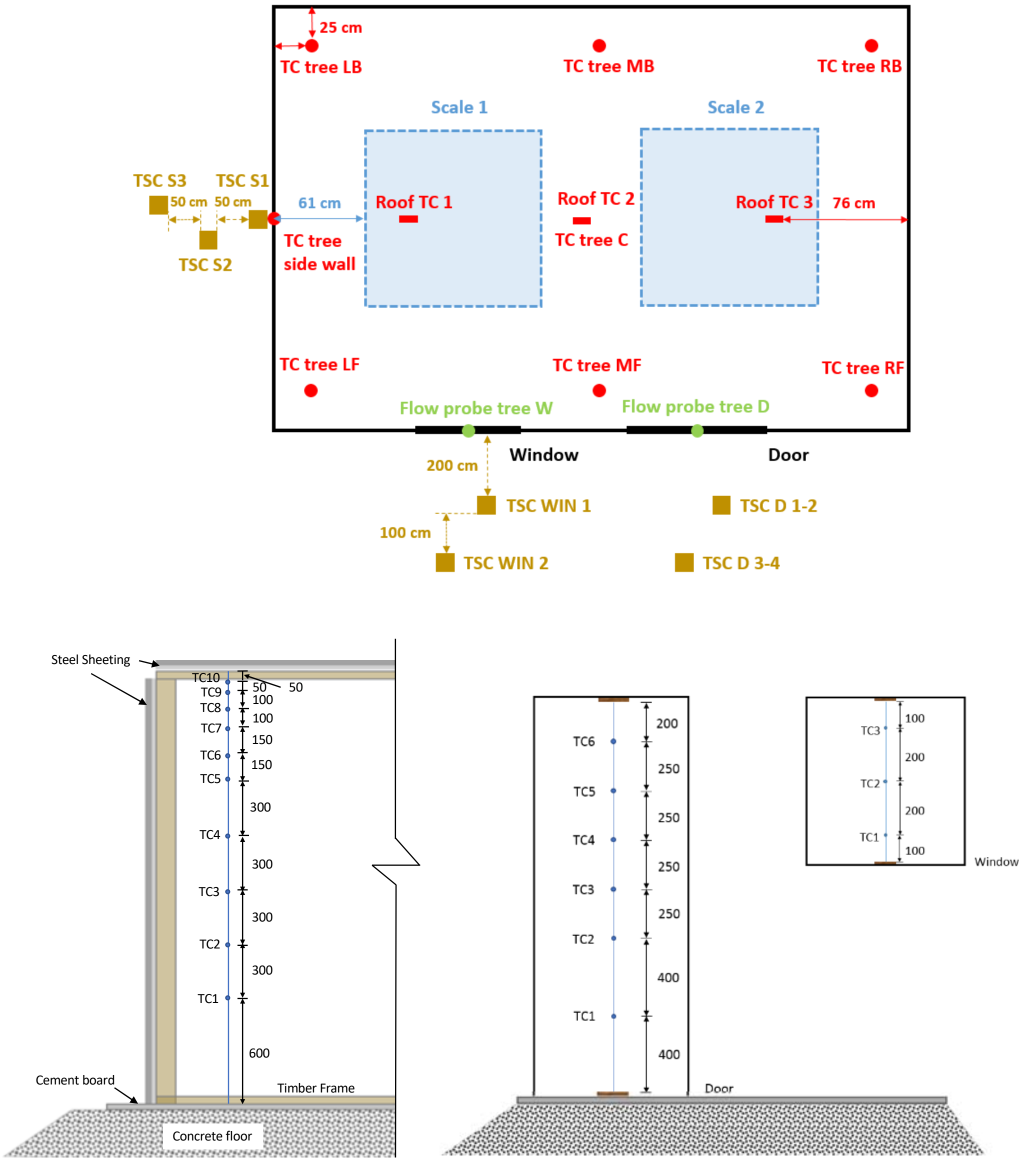


Fig. 3. The plain view of the measurement instruments and TC locations.

Outside the compartment, Thin Skin Calorimeters (TSCs) [18] were employed to measure irradiation (incident radiant heat flux). Two TSCs measured irradiation from the window at a height of 1.6 m off the floor, which is the mid-height of the window at a distance of 2 m and 3 m from the window, respectively. Four TSCs were placed in front of the door; two at heights of 1.6 m and two at 2.5 m, again at distances of 2 m and 3 m, respectively. Three further TSCs were placed next to the side wall at distances of 0.05 m, 0.5 m and 1.0 m, respectively, all at 1.2 m high. All temperature, flow, and mass loss data were logged at a rate of 0.2 Hz.

The fire experiments were conducted under a 10 MW large fire calorimeter hood (7.62 m (25 ft) off the floor, 7.62 m (25 ft) diameter hood inlet) in the burn hall of Underwriter Laboratories, Chicago, US. The extraction gas velocity was controlled between 12-16 m/s during the experiment. The convective and total heat release rate (HRR) were recorded every second from the time of ignition.

Three cameras were placed in front and beside the dwelling to record the burning process. One camera was placed to capture the flame heights out of the openings, one placed to capture the flame lengths out of the openings, and one was placed to observe the burning of the cribs within the compartment. Other handheld cameras were used to capture significant events during the experiments (i.e. roof collapse).

Gas concentrations (O_2 and CO_2) were measured approximately 10 cm below the ceiling in the corners of the compartments, at perpendicular distances of 25 cm from each of the long and short walls.

The experiments were ended either when; a) the fire had completely burnt out, b) the structure had collapsed (wall and roof), or c) if the calorimetry equipment was in danger of being damaged (max HRR being exceeded or temperature within the extract ducts).

3. Experimental results and discussions

3.1 The internal fire dynamics

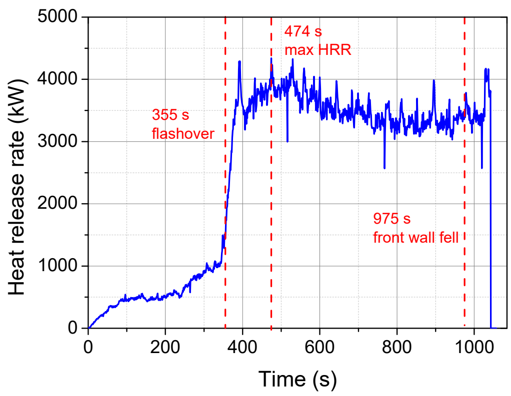
The section presents the experimental measurements of flashover occurrence, HRR, wall and gas temperatures and velocity measured inside the compartment. The baseline experiment (BL) is shown as a reference first (Fig. 4.). The flashover has different definitions, and in this work, it is defined as the sudden propagation of flame out of the compartment openings [17].

a) 355 s

b) 600 s

c) 975 s

d) 1049 s



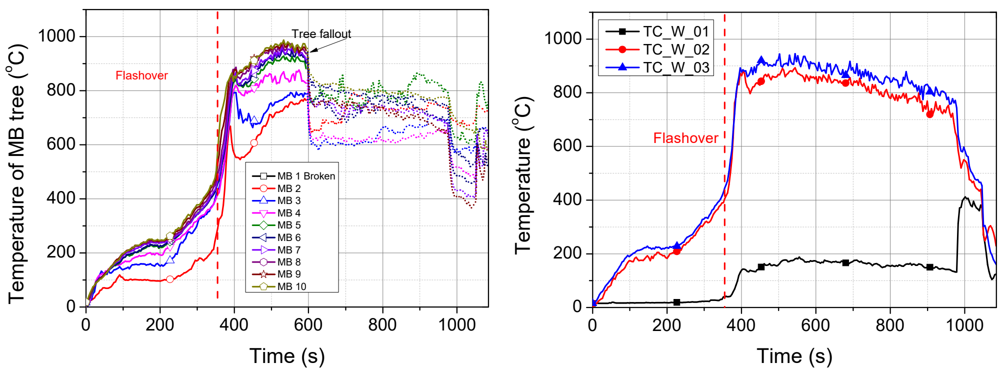
e)

Fig. 4. The burning behaviour and the measured HRR, BL; a) 355 s flashover occurrence; b) 600 s stable burning; c) 975 s front wall fallout; d) 1049 s dwelling collapse; and e) The total HRR measured by the hood.

In BL, flashover occurred at 355 s after ignition. The temperature in the smoke layer at this time just reached around 525 °C in Middle Back (MB) tree which agrees well with another indication of flashover [19]. What is significant is that the flames first came out from the leakage at the upper edge in the front wall above the door (see Fig. 4(a)), significantly different from well-sealed compartments in previous studies [20, 21]. Four seconds later, the wood frame of the door and window ignited with flame ejecting out. At 975 s, the front wall inclined and then the whole dwelling collapsed at 1049 s. The photographs at these times are shown in Fig. 4(a)-(d). In addition, the HRR measured by the hood from ignition to water extinguishment (1085 s) is shown in Fig. 4(e) and it can be seen that the flashover time agrees well with the visual observations. Between 340 to 390 s, the HRR increased significantly from 1.0 MW to 4.3 MW. The maximum HRR in the experiments is 4.3 MW at 474 s. The maximum HRR in post-flashover compartments can be calculated [17]:

$$Max\ HRR = \dot{m} \times Q_w = 0.09 A_v \sqrt{H_v} Q_w \tag{1}$$

where Q_w is the heat of combustion of wood, assumed as 17.5 MJ/kg; $\dot{m}$ is the mass loss rate of the crib (g/s). The calculation result is 4.1 MJ, slightly smaller than the measured value. In the ventilation control stage, the incoming air through the leakages in the lower layer, not counted in Eq. (1), results in a higher HRR than the theoretical value.



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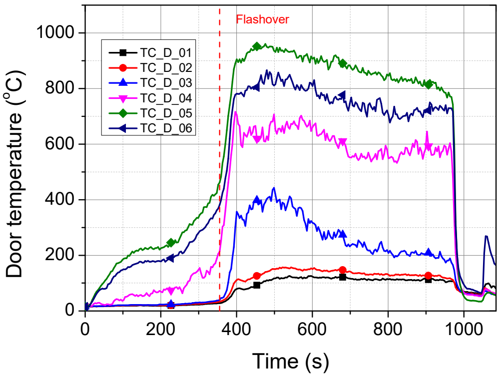

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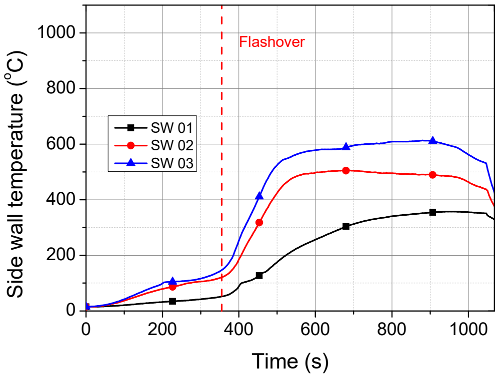

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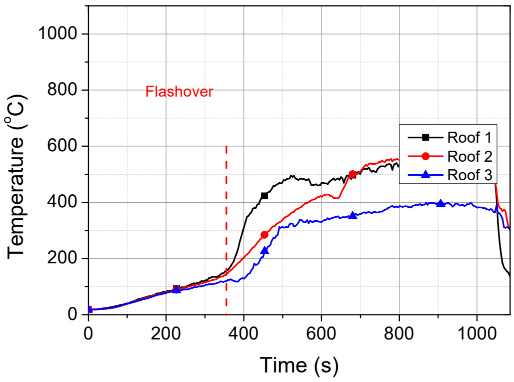


e)

Fig. 5. Temperature measurement in BL experiment; a) for the MB TC tree; b) at the window opening; c) at the door opening; d) side wall; and e) roof.

The gas temperatures measured after flashover in experiment BL are unfortunately unreliable due to an instrumentation mounting resulting in all the six trees falling down at or very soon after flashover. This issue was fixed in all other experiments. The MB TC tree was the most reliable and is shown in Fig. 5(a), which suggests that the maximum temperature may reach nearly 990 °C soon after flashover. The flashover occurrence also agrees wells with sudden temperature increase. The theoretical temperature calculation is according to the following equation [22]:

$$T_{\max} = \frac{6000(1-e^{-0.1\Omega})}{\sqrt{\Omega}} \tag{2}$$

$$\Omega = \frac{A_T - A_V}{A_V \sqrt{H_V}} \tag{3}$$

where $T_{\max}$ is the maximum gas layer temperature; A_T is the total area of the compartment internal surfaces; A_V is the opening areas (discounting the leakage caused by construction of the dwellings); H_V is the weighted height of the ventilation [23]. Equation 2 calculates the maximum temperature as 1210 °C which is larger than the measured temperature. The radiative losses through the thin metal boundaries may account for the relatively low gas temperature compared with calculations. More gas temperatures will be shown for the other experiments.

The temperatures at the door, window, wall and ceiling are shown in Fig. 5(b)-(e). It can be seen that temperature at the door and window demonstrate good gradient with respect to height and kept relatively stable post-flashover, suggesting a stable neutral plane height at the opening. The wall and ceiling temperature increase quickly approximately 30 s after flashover occurrence. Besides the time needed for heat transfer from the gas to the wall, the radiative losses at the ambient side of metal wall panels are significant due to their relatively high temperature and thermally thin material properties.

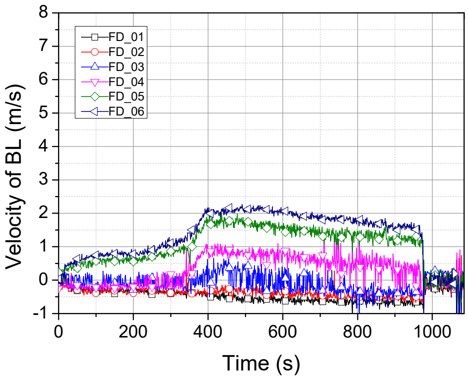
The neutral plane height can be determined theoretically by the following equations [24]:

$$h = \frac{H}{1 + (\rho_a / \rho_g)^{1/3}} \tag{4}$$

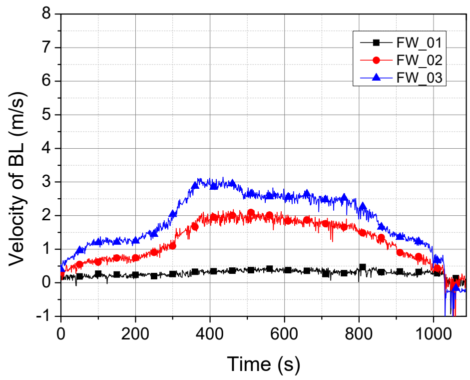
$$\rho_g = \frac{PM}{RT_g} \tag{5}$$

where h and H are the neutral plane height and total vent height; T_g and ρ_g are enclosure gas temperature and density; ρ_a is the density of air outside the room. With the assumption of the compartment temperature of 987 °C (maximum temperature measured), the neutral plane height is 0.75 m for the door.

The measured air velocities are shown in Fig. 6. It can be seen that the neutral plane height in experiment BL is around 1.05 m (FD_03) after flashover, which is larger than prediction. This may be due to the leakage at the construction joints that allows smoke and flame to eject from more openings the planned. In addition, the maximum out air velocity is around 2 m/s that is significantly smaller than previous full-scale compartment fire [21]. This is assumed to be caused by the leakage also. This was confirmed in experiment BL-NL, where the construction joints were sealed to have no leakage. It can be seen that the neutral plane height is lower than the Baseline experiment as FD_03 is evidently outflow (positive) while in Baseline the gas at this location is nearly zero or sometimes below zero. However, its neutral plane height (0.80-1.05 m) is still larger than the theoretical calculation. In BL-NL the maximum velocity at door and window were approximately 5 and 7 m/s, respectively, as shown in Fig. 6.



a)



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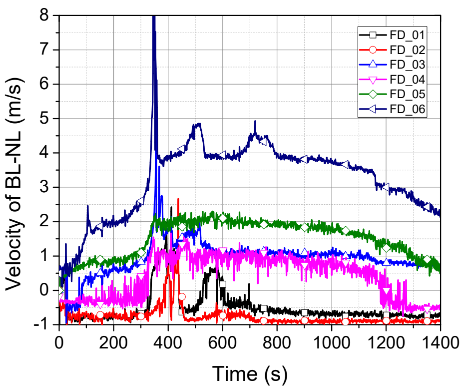

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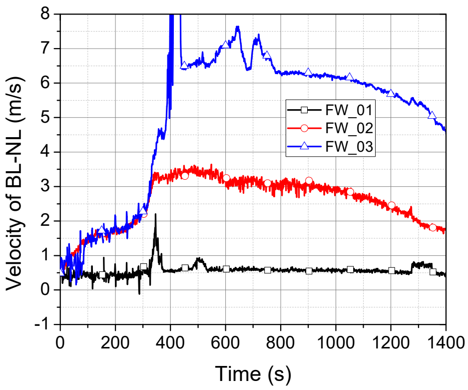


d)

Fig. 6. The gas velocities at the door and window; a) BL door; b) BL window; c) BL-NL door; d) BL-NL window.

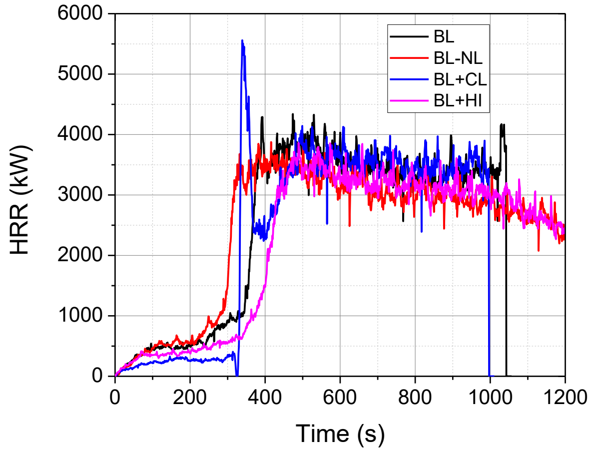
The HRR comparison from four experiments is shown in Fig. 7 (a) and summarised in Table 2. BL experiment shows larger HRR than BL-NL and BL+HI after flashover, which both had better-sealed boundaries. In BL-NL, due to the sealant of the leakage, the flame first ejected (i.e. flashover) from the door at 311 s, which is significantly earlier than the other 3 experiments. The energy loss from the upper leakage plays a key role in the difference.

Table 2. Summary of total HRR measured by the hood.

No.	Time to flashover (s)	HRR at flashover (kW)	Time to peak HRR (s)	Peak HRR (kW)
BL	355	1445	474	4339
BL-NL	311	2514	416	3876
BL+CL	300;395	349;2392	339	5560
BL+HI	417	2193	489	3861

* BL represents Baseline; BL-NL for Baseline - No Leakage; BL+CL for Baseline + Cardboard Lining; BL+HI for Baseline + High Insulation.

In BL+CL, two flashovers (defined as flame out) occurred, caused by the cardboard and wood crib, respectively. The cardboard flashover resulted in a much larger ejected flame (approximately 1 m horizontal, 3 m vertical); this has a larger fire spread potential than the unlined BL experiment as flame impingement and radiation are the primary urban fire spread mechanism [25]. However, the cardboard burning did not substantially change the fire dynamics within the compartment as it did not ignite the wood crib surface as demonstrated in Fig. 7(b), thus its HRR curve mimics the other experiments post-flashover. The heavily insulated wall in the BL+HI experiment significantly delayed the flashover occurrence, by approximately 60 seconds compared to the BL experiment. Flashover occurred between 5-7 min after ignition, with HRR peaks of around 4 MW, with BL+CL being an exception.



a)

b)

Fig. 7. a) Comparison of HRR; and b) the different burning phenomenon in BL+CL before (left), during (centre) and after (right) cardboard flashover.

Assuming the heat of combustion of the wood of 17.5 MJ/kg and 100% combustion efficiency, the HRR of BL+HI calculated from mass loss rate measured by the two scales are presented in Fig. 8 as an example. It can be seen that the two cribs contributed similarly to the total HRR in the whole burning process. The HRR estimated based on the mass measurements by the scales and hood measurement are very similar, while larger value of HRR measured by the scale. The thick wall in BL+HI absorbed significantly more energy than the other experiments from the burning wood crib. The other BL, BL-NL and BL+CL experiments expressed the small difference between HRR measured from scales and calorimeter. However in each of these three experiments, data was lost at least one of the scales cables connected to the logging equipment burnt through – work on cleaning and interpreting this data is ongoing.

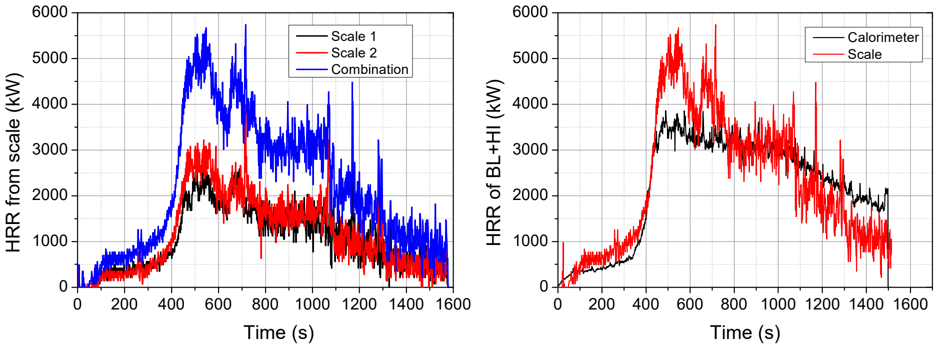
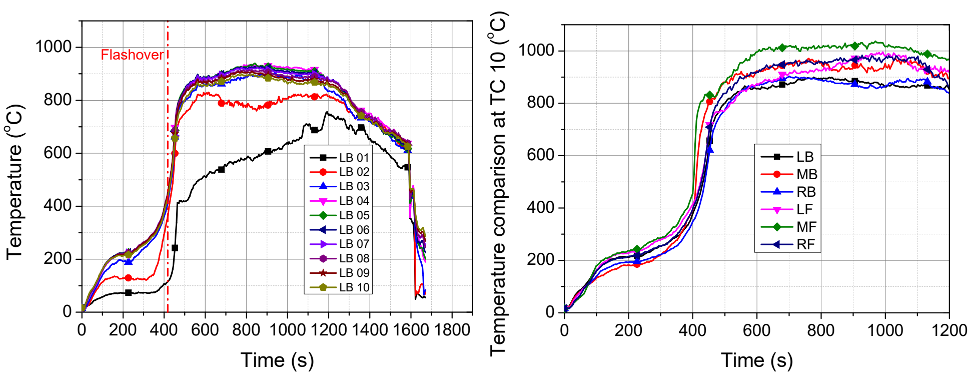
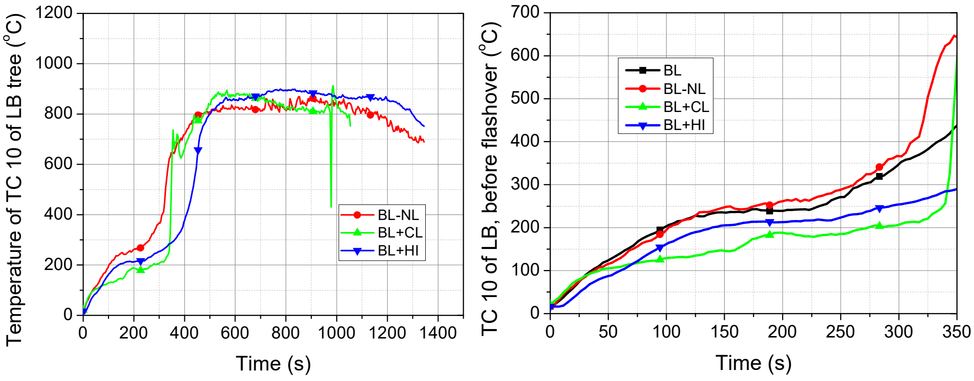


Fig. 8. The HRR for the BL+HI experiment, measured by scales inside the compartment (left) and a comparison to the HRR captured by the hood (right).

An example set of gas temperatures measured at LB (Left Back) TC tree inside the BL+HI are shown in Fig. 9(a). The compartment temperatures are governed by the heat released in the compartment and the heat loss through the boundaries [26], thus the temperatures follow the trends of heat release rate. The exception to this are TCs 1 and 2 which are below 0.9 m and are below the neutral plane measured at the door. The other measured temperatures (TCs 3-10) follow very similar trends reaching as high 900 ºC.



(a)



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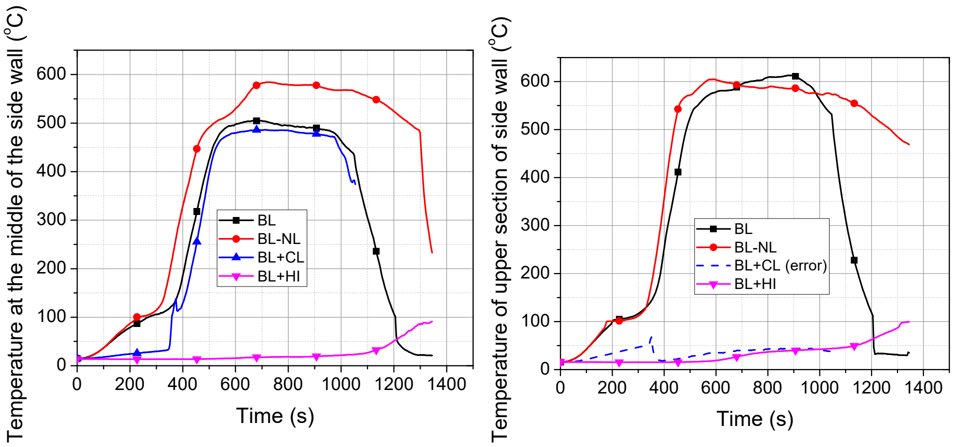
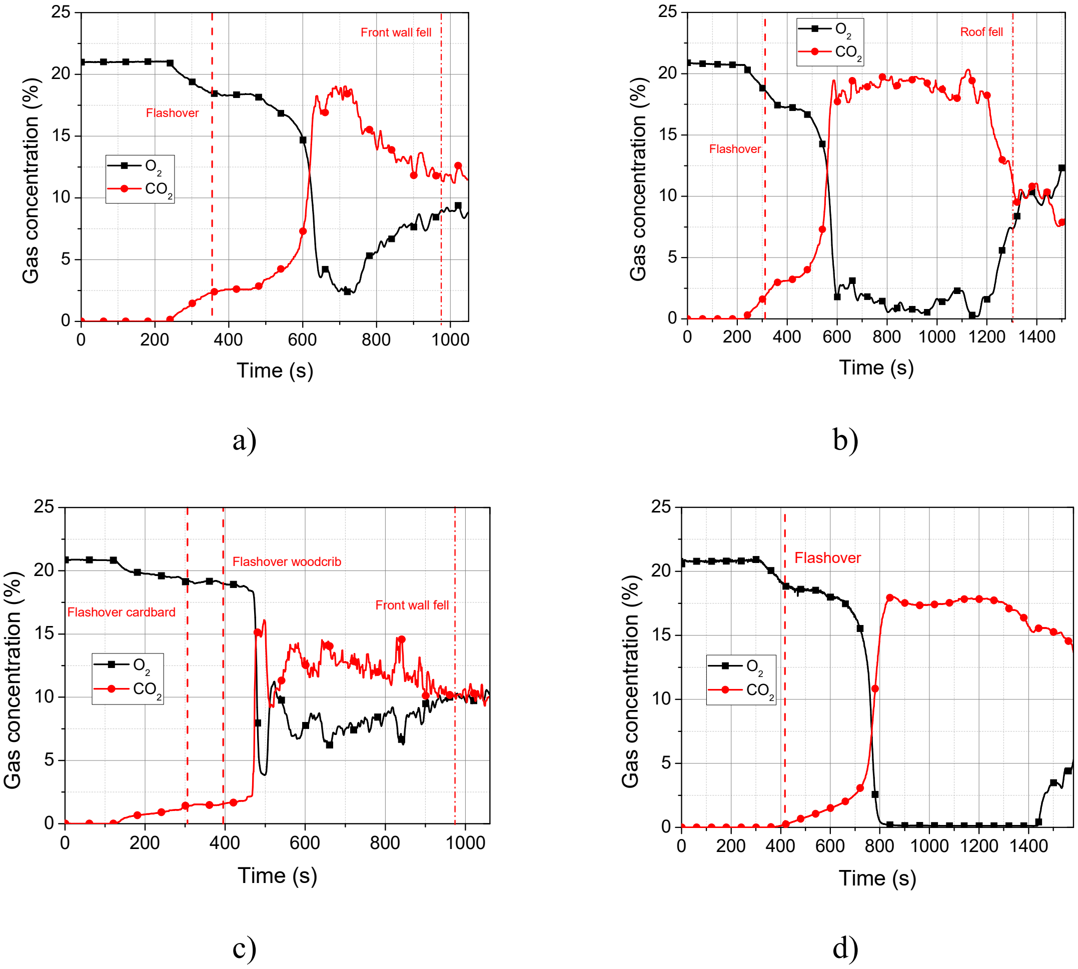


(c)

Fig. 9. The gas and side wall temperature comparison; a) Temperatures of the six inner thermocouple trees in in test BL+HI; b) Temperatures of TC10-LB in tests BL-NL, BL-CL, and BL-HI; and c) Wall temperature comparison for all the tests.

Through a comparison of TC 10 between all the TC trees, it can be found that the back corners temperature are comparatively low to those at front (closer to the openings) which are approximately 100-200 °C higher, with the MF (Middle Front) tree experiencing the highest temperatures. Fig. 9(b) clearly shows the similarity of temperatures between the experiments (BL excluded due to the aforementioned mounting failure). However, BL temperature before flashover was added for comparison and it can be seen that before flashover, the temperature of BL is around 50 - 100 °C higher than BL+HI.

The middle and upper temperatures of the side wall (ambient side) in the four experiments are compared in Fig. 9(c). The wall temperatures in BL, BL-NL and BL+CL increased rapidly to around 600 °C and corresponds well with the gas temperature, while the wall temperature of BL+HI are significantly smaller than other three experiments. For both gas temperature and wall temperature, the effect of cardboard lining burning in BL+CL is found to be limited.



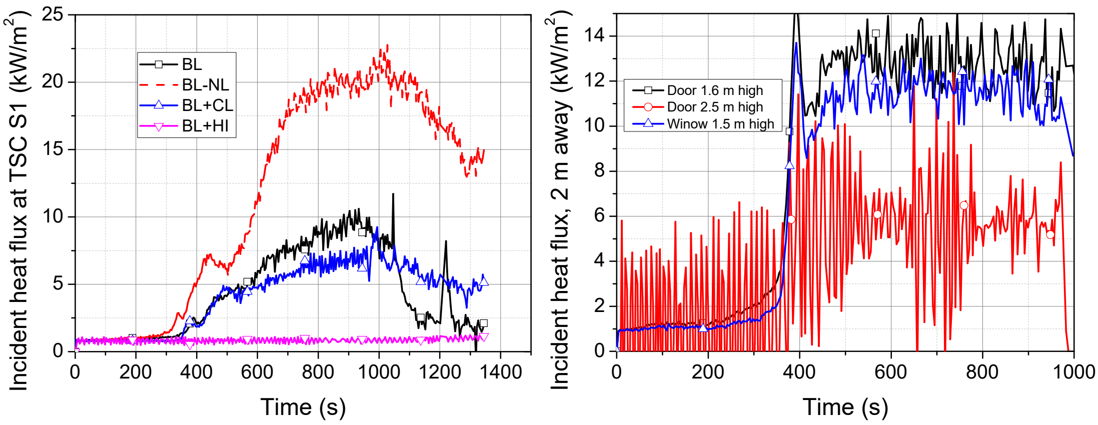
a) b) c) d)

Fig. 10. The gas concentration; a) Left back corner, BL; b) Same location as top flow probe of window, BL-NL; c) Left back corner, BL+CL; and d) Behind the window, 5 cm below ceiling, BL+HI.

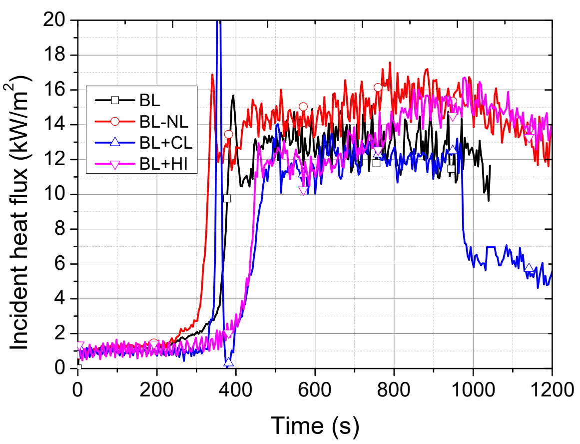
The concentrations of the gas of all the experiments are shown in Fig. 10. In BL, combustion internally was relatively well maintained for approximately 5 minutes. This is due to the leakage at the boundaries allowing more oxygen into the compartment; more oxygen will cause more burning and higher HRR post flashover. The influence of the leakage at the boundaries on the oxygen concentration is evident when comparing BL and BL-NL. In addition, oxygen and carbon dioxide normally started to decrease and increase, respectively, when flashover occurred. The burning of the cardboard lining can be observed in the oxygen and carbon dioxide concentrations as shown in Fig. 10(c), whilst the influence of heavily insulating the compartment walls leads to almost no internal combustion within the smoke layer due to a complete lack of oxygen.

3.2 External measurements

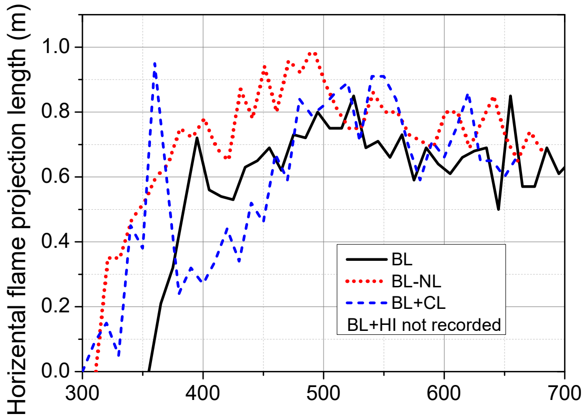
Fire spread between the dwellings is a crucial issue for fires in informal settlements. To investigate this issue, the incident heat flux and flame lengths were measured outside the compartment. The TSCs located 5 cm away from side wall are compared in Fig. 11(a). It can be seen that the heat fluxes of BL and BL+CL are similar with a maximum value of 10 kW/m^2, while BL+HI show very small value below 1 kW/m^2. However, the heat flux recorded in BL-NL is much higher than the other experiments; this is also observed in the TSCs that are 0.5 m and 1.0 m away from the wall (not presented).



a) b)



c)



d)

Fig. 11. The comparison of incident heat flux and flame length outside the dwellings; a) Side wall TSC; b) Door and window in BL experiment; c) Incident HF at door, 2 m away and 1.6 m high; and d) The horizontal length of the flame.

The temperature of the side wall is similar to other experiments (Fig. 9(c)), but it was found in the video that more flames came out from the overlap area of the metal panels after buckling than was observed in the other experiments. However, it should be noted that in all experiments, the peak incident heat flux measured by TSC S3 (1 m away from the wall) is below 7 kW/m^2. From the authors' own materials database, this heat flux is only large enough to ignite the mattress foam, with critical heat flux of 6-7 kW/m^2 [11]. Thus, if the wall does not collapse and does not excessively deform, then the possibility of fire spread caused by radiation from a wall is relatively low.

Fig. 11(b) shows, for BL, the measured heat fluxes from the door and window at a distance of 2 m. It can be clearly seen that the door and window heat fluxes are similar and the values at the height of 1.6 m (approximately 11.5 kW/m^2 and 12.5 kW/m^2 average post-flashover) are considerably larger than the one at 2.5 m high (approximately 6 kW/m^2 average post flashover). In the other experiments, the trends are identical, thus the values of TSC D 1 (2 m away and 1.6 m high) is selected to compare between the four experiments, as shown in Fig. 11(c). It was found that BL-NL and BL+HI have larger heat fluxes (approximately 15.5 kW/m^2 and 14.5 kW/m^2 average post-flashover, respectively) due to a better-sealed boundary resulting in larger horizontal flame projection length. The horizontal flame lengths were recorded by the camera at side view (excluding BL+HI where the camera did not record), as shown in Fig. 11(d). After flashover, the flame length was measured every 10 s, and it was found that the BL-NL has the largest luminous length of 1.0 m among the experiments, while 0.85 m and 0.95 m for BL and BL+CL respectively. By empirical expression for projection length [17, 23], the calculated flame length is 1.5 m (without an above wall) and 1.1 m (with an above wall) which are both larger than experimental observation. This could be due to the different flame recognitions in the plume (540 °C was used in equations) and the determination of the wall above the opening (borderline in experiments).

3.3 Short discussion

As illustrated in the above section, BL (with thermally thin walls) reached the fully developed stage before BL+HI (with thermally thick walls). Compartments with thermally thin walls can easily absorb and lose heat to the outside due to the very high conductivity of steel, therefore, this relatively unexpected behaviour could be related to the heat transfer/heat balance of the walls in each case. To explain this, it is important to look at the wall temperatures to understand the walls' heat balance for each case. As it is presented in Fig. 9(c), the outer wall temperature for BL (thermally thin walls) at pre-flashover may reach as high as 100 °C. This indicates that the thermally thin walls were heated up very quickly via the top gas layer and the heat was conducted rapidly from the top to the bottom of the walls. At that stage, the walls and ceiling were acting as five radiant panels which are radiating to the outside (heat losses) and re-radiating to the inside (heating up the compartment) as presented in Fig. 12 (ignoring the re-radiation from the hot top section of the wall to the cooler walls' sections below). This re-radiation highly affected the growth phase progress by radiating heat to the cool gases and wood cribs within the compartment, thus enhancing the flame spread on the cribs and eventually causing a faster flashover. The thermally thick walls, however, absorbed significantly more of the heat and keep relatively low temperature, thus re-radiate less back to the fuel. If for creation of a numerical model, modelling lateral heat transfer in the solid for thin obstructions may be needed.

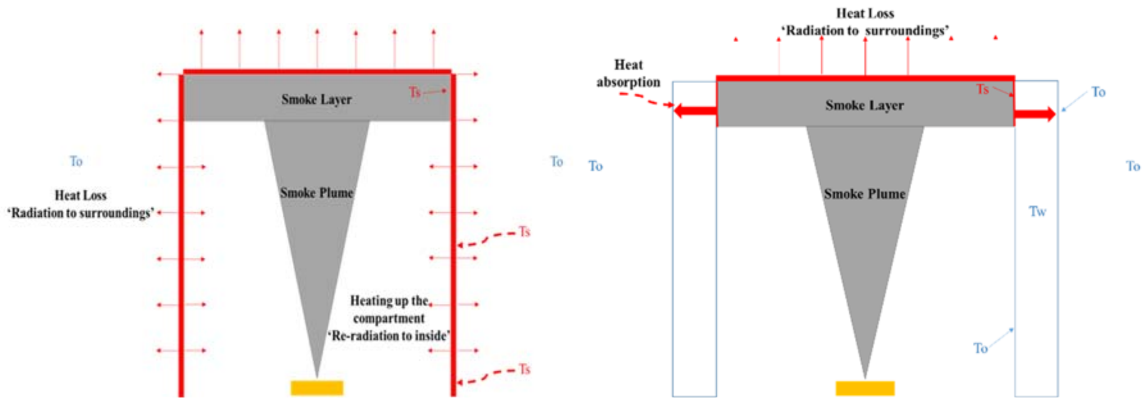


Fig. 12. Heat transfer explanation (Thermally thin, left) and (Thermally thick, right), where T_s is smoke temperature and T_o is the ambient temperature.

It should also be noted that the collapse of the structure may also have significant influence on the fire spread. In this work, it was found BL+HI did not collapse due to the thick walls and the insulation around the structural timbers of those walls, however, the roof collapse occurred in all the other three experiments which is very different phenomenon from normal dwellings, as shown in Fig. 13.

(a) BL 1088s (b) BL-NL 1514 s (c) BL+CL 1046 s (d) BL+HI 1581 s

Fig. 13. The final stage of the burning dwellings (BL for Baseline; BL-NL for Baseline - No Leakage; BL+CL for Baseline + Cardboard Lining; BL+HI for Baseline + High Insulation).

4. Conclusions

In this work, four full-scale experiments were conducted under large hood calorimeter to investigate the influence of different boundary conditions of informal settlement type dwellings. The leakage existence, lining materials and wall insulation condition were considered. Important parameters of compartment fires were measured and presented, such as the HRR, gas and wall/ceiling temperature, gas concentration, flow velocity and radiation incident heat flux. The primary conclusions are as follows:

- The experimental boundary conditions significantly differ regarding the flashover occurrence: sealing leakage makes the flashover occur earlier; combustible lining materials such as cardboard can cause double flashovers; and wall insulation may significantly delay the flashover.
- The cardboard lined walls commonly found in informal settlement dwellings increase the risk of flame spread potential, achieving large flame lengths and much higher HRR albeit for short time, however the linings effects on the internal compartment dynamics is limited.
- Heavily insulated non-combustible walls increase the structural stability of the dwellings and keep the outside surface below 150 ^{o}C, with smallest peak HRR, however, it increases the internal temperatures post-flashover.
- Compared with theoretical calculation, informal settlement dwellings have higher peak HRR but with lower temperature, caused by the leakage at connections.
- Wall or roof collapse should not be neglected as a potential fire spread mechanism.

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Figure captions

Fig. 1. The structural dimension of the dwellings; a) from informal settlements in Cape Town, and b) our test specimen dwelling.

Fig. 2. View of the compartments prior ignition. (a) Experiment 1; (b) Experiment 2; (c) Experiment 3; (d) Experiment 4

Fig. 3. The plain view of the measurement instruments and TC locations.

Fig. 4. The burning behaviour and the measured HRR, BL; a) 355 s flashover occurrence; b) 600 s stable burning; c) 975 s front wall fallout; d) 1049 s dwelling collapse; and e) The total HRR measured by the hood.

Fig. 5. Temperature measurement in BL experiment; a) for the MB TC tree; b) at the window opening; c) at the door opening; d) side wall; and e) roof.

Fig. 6. Fig. 6. The gas velocities at the door and window; a) BL door; b) BL window; c) BL-NL door; d) BL-NL window.

Fig. 7. a) Comparison of HRR; and b) the different burning phenomenon in BL+CL before (left), during (centre) and after (right) cardboard flashover.

Fig. 8. The HRR for the BL+HI experiment, measured by scales inside the compartment (left) and a comparison to the HRR captured by the hood (right).

Fig. 9. The gas and side wall temperature comparison; a) Temperatures of the six inner thermocouple trees in in test BL+HI; b) Temperatures of TC10-LB in tests BL-NL, BL-CL, and BL-HI; and c) Wall temperature comparison for all the tests.Fig. 10. The gas and side wall temperature comparison; a) Temperatures at the inside six trees; b) The TC 10 comparison of LB; and c) Side wall temperature comparison.

Fig. 10. The gas concentration; a) Left back corner, BL; b) Same location as top flow probe of window, BL-NL; c) Left back corner, BL+CL; and d) Behind the window, 5 cm from ceiling, BL+HI.

Fig. 11. The comparison of incident heat flux and flame length outside the dwellings; a) Side wall TSC; b) Door and window in BL experiment; c) Incident HF at door, 2 m away and 1.6 m high; and d) The horizontal length of the flame.

Fig. 12. Heat transfer explanation (Thermally thick, left) and (Thermally thin, right), where T_s is smoke temperature and T_o is the ambient temperature.

Fig. 13. The final stage of the burning dwellings (BL for Baseline; BL-NL for Baseline - No Leakage; BL+CL for Baseline + Cardboard Lining; BL+HI for Baseline + High Insulation).

Highlights:

- Full-scale experiments indicate the fire development and spread in the informal settlement
- Compartment boundary conditions significantly differ the flashover occurrence
- Informal settlement dwellings have higher peak HRR and but lower temperature
- The collapses of the wall or roof should not be neglected
- Current analytical equations are not capturing informal settlement burning behavior